Electronic Systems

- Active components (transistors) as switches
## Transistors Allow “Low Power” to Control “High Power”

<table>
<thead>
<tr>
<th>“High Power” (≥ 500 mW)</th>
<th>“Low Power” (&lt; 50 mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ &gt;100 mA, &gt;5V</td>
<td>▪ ~10 mA, 3.3 or 5 V</td>
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<tr>
<td>▪ Actuators</td>
<td>▪ Microcontrollers</td>
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<tr>
<td>• DC motors</td>
<td>• Controlling motors</td>
</tr>
<tr>
<td>• Stepper motors</td>
<td>• Reading sensors</td>
</tr>
<tr>
<td>• Solenoids</td>
<td>• Processing controllers</td>
</tr>
<tr>
<td>▪ Some sensors</td>
<td>▪ Some sensors</td>
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<tr>
<td>• IR sensors</td>
<td>▪ Small LEDs</td>
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<tr>
<td>▪ Big LEDs</td>
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</table>
MECHATRONIC SYSTEMS REQUIRE POWER AMPLIFICATION

- Many electro-mechanical loads have a low resistance, requiring an emphasis on current gain.
- Unlike power amps for communication and audio systems, a DC response is often necessary.
- For most mechanical systems, power stage bandwidth (−3 dB) is rarely above 10 kHz.
OPTIONS FOR ACHIEVING AMPLIFICATION?

When driving a motor, should we operate a transistor in linear amplification mode or saturation mode?

- Linear amplification controls speed with the base current or gate voltage
- Saturation controls speed with duration of on/off periods
  - Similar to modulation
  - Motor acts as a low-pass filter

Define efficiency in terms of power: \[ \eta = \frac{P_{out}}{P_{in}} \]
HOW MUCH POWER DO YOU NEED?

Low Power NPN (2N3904)

\[ i_c \text{ (max)}: 200 \text{ mA} \]
\[ P_D: 625 \text{ mW} \]
\[ \beta: 100-300 \]

High-Power NPN (2N3055)

\[ i_c \text{ (max)}: 15 \text{ A} \]
\[ P_D: 115 \text{ W} \]
\[ \beta: 20-70 \]

Will likely need a heat sink!
A DARLINGTON PAIR CAN PROVIDE HIGH AMPLIFICATION

Medium Power Darlington Pair (TIP120)

- $i_C$ (max): 4 A
- $P_D$: 65 W
- $\beta$: 2500

AMPLIFIERS CAN PROVIDE DIRECTIONAL CONTROL

- Push-Pull (class B) power (output) stage
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- Push-Pull (class B) power (output) stage
AMPLIFIERS

“Class A”

- Transistor in linear amplification region at all times
- Requires only a single transistor; simple to build
- *Maximum* efficiency of 25%

![Image](https://en.wikipedia.org/wiki/File:Electronic_Amplifier_Class_A.png)
AMPLIFIERS

“Class B”

- Push-pull amplifier
- Subject to "crossover distortion"
- Maximum efficiency of 78%
- Typical efficiency of 70%
“Class D” amplifier

- Transistors act in saturation mode (switching on and off)
- Motor acts as low-pass filter
- Maximum theoretical efficiency of 100%
- Typical efficiency of 80% to 95%
WHERE TO PLACE THE LOAD?

- Turn-on/off currents to actuators and sensors – controlling the current flow (turning on/off a device)
- Can be connected directly to a digital output (if the digital output stage can supply the required base current)
DIGITAL DEVICE OUTPUTS MAY BE OPEN-COLLECTOR OF A BJT

- Base-emitter junction of BJT transistor turned on/off with digital output
- Need to connect the output (collector) to a voltage source through pull-up resistor $R_P$ to obtain anticipated output
- Can drive an analog device if capable of sinking adequate current. If not, need to use another more “powerful” transistor
DRIVING INDUCTIVE LOADS REQUIRES EXTRA CARE

- Inductive loads are very common in electro-mechanical devices, e.g. motors, solenoids, and voice-coil motor etc.

- A large voltage will build-up across the inductor when the inductor current is switched off. This voltage can be large enough to damage the transistor (inductor kickback)
Driving inductive loads requires extra care.

\[ V_L = L \cdot \frac{d}{dt} i_L \]

Negative \( V_L \) means the connection between inductor L and resistor R is at a higher voltage than the source voltage +V.

Breakdown voltage.
A FREEWHEELING DIODE CAN SHUNT THE INDUCTIVE LOAD

- Also called a flyback, kickback, or snubber diode
- Induced current circulates in a closed loop until dissipated
- Protects the transistor!
OPERATIONAL AMPLIFIERS PERFORM MANY USEFUL TASKS

741 Op-amp – an industry standard

- Addition
- Subtraction
- Amplification
- Integration
- Filtering

Image: http://www.tandyonline.co.uk/741-operational-amplifier.html
- Output driven in positive direction when $E^+ > E^-$
- Output driven in negative direction when $E^- > E^+$

$$E_O = G_O(E^+ - E^-)$$
OP-AMP MAY BE MODELLLED AS A LOAD AND CURRENT SOURCE
WHAT’S INSIDE?

741 op-amp schematic

Input Differential Amplifier

Output Amplifier
OP-AMP CHARACTERISTICS

Ideal

- Infinite High Open Loop Gain
- Infinite High Input Impedance
- 0 Low Output Impedance
- Infinite High Bandwidth
- 0 Zero Offset

Reality

- $10^4$ to $10^6$
- 300 kΩ to 1000 GΩ
- 10 Ω to 5 kΩ
- (150 – 200 Ω typical)
- 0.5 to 15 MHz
- 0.1 to 5 mV

Implications:

- Seldom used in open-loop mode
- Almost exclusively used in feedback mode
If $R_i = \infty$, input currents are zero

If input currents are zero, $E^- = E^+$
THE GOLDEN RULES:

1. The inputs draw no current
   - Op-amp draws very little input current (0.5 mA for a 741C); we round it to zero for practical calculation.

2. Inverting and non-inverting inputs remain at the same voltage
   - The op-amp will do whatever is necessary to make the voltage difference between the inputs equal zero. It “looks” at the input terminals and changes its output voltage such that the external feedback network brings the input difference to zero.

*These rules only apply when the op-amp is operated:*
   - Within its listed specifications
   - In negative feedback mode
TYPICAL USAGE

Negative feedback in this example, $V_{out} = V_{in}$

Q: What type of circuit is this? How can it be used?
OP-AMP EXAMPLES

- Inverting Amplifier

\[
\frac{E_i - E^-}{R_1} = I_i = I_F = \frac{E^- - E_O}{R_2}
\]

\[
E^- = E^+ = 0
\]

\[
\frac{E_O}{E_i} = -\frac{R_2}{R_1} \Rightarrow E_O = -\frac{R_2}{R_1} E_i
\]

- Non-inverting Amplifier

\[
E_i = \left(\frac{R_1}{R_1 + R_2}\right) E_O \Rightarrow E_O = \left(\frac{R_1 + R_2}{R_1}\right) E_i
\]

\[
E_O = \left(1 + \frac{R_2}{R_1}\right) E_i
\]

Q: What if \( R_2 = 0 \) and \( R_1 \to \infty \)?
OP-AMP EXAMPLES

- Low Pass Filter

\[
Z = \frac{1}{R_2 + j\omega C} = \frac{R_2}{1 + j\omega R_2 C}
\]

\[
\frac{E_O}{E_i} = -\frac{R_2}{R_1} \cdot \frac{1}{j\omega R_2 C + 1}
\]

- High Pass Filter

\[
Z = R_1 + \frac{1}{j\omega C} = \frac{j\omega R_1 C + 1}{j\omega C}
\]

\[
\frac{E_O}{E_i} = -\frac{R_2}{R_1} \cdot \frac{j\omega R_1 C}{j\omega R_1 C + 1}
\]
Thevenin Equivalents:

Source

Load
OUTPUT IMPEDANCE LOOKS “BACK” FROM OUTPUT

Source

Load
INPUT IMPEDANCE LOOKS “FORWARD” FROM INPUT

Source

Load
Input and output impedances may be vastly different!
**FEEDBACK ALTERS OP-AMP IMPEDANCE**

Open-loop Input Impedance: 2 MΩ  
Closed-loop Input Impedance: 2 TΩ  
Open-loop Output Impedance: 75 Ω  
Closed-loop Output Impedance ≈ 0 Ω

Without op-amp:  
\[ V_L = \frac{4 \Omega}{2004 \Omega} \cdot V_S = .002 \cdot V_S \]

With op-amp:  
\[ V_L \approx V_S \]  
(as long as output is not saturated)
HIGH INPUT IMPEDANCE IS USUALLY DESIRED

Want $Z_L \gg Z_S$:

$$V_L = \frac{Z_L}{Z_S + Z_L} V_S \rightarrow 1$$
IMPEDEDANCE MATCHING MAXIMIZES POWER TRANSFER

\[ P_L = V_L i = \left( \frac{Z_L}{Z_s + Z_L} \right) V_s \left( \frac{V_s}{Z_s + Z_L} \right) = \frac{V_s^2}{Z_s^2 + 2Z_s + Z_L} \]

\[ \frac{d}{dZ_L} \left( \frac{Z_s^2}{Z_L} + 2Z_s + Z_L \right) = 1 - \frac{Z_s^2}{Z_L^2} = 0 \implies \frac{Z_s^2}{Z_L^2} = 1 \]

\[ \therefore Z_s = Z_L \]
MAXIMIZING POWER TRANSFER DOES NOT MAXIMIZE EFFICIENCY!

\[ P_S = V_S i \]
\[ P_L = V_L i = \frac{Z_L}{Z_S + Z_L} V_S i \]

\[ \eta = \frac{P_L}{P_S} = \frac{Z_L}{Z_S + Z_L} \]

At max power transfer, \( Z_L = Z_S \) and \( \eta = 0.5 \)

However, \( \eta > 0.5 \) when \( Z_L > Z_S \)
POWER LOSS VARIES WITH IMPEDANCE RATIO

\[ \eta = \frac{P_L}{P_S} = \frac{Z_L}{Z_S + Z_L} \]
POWER LOSS IS MINIMIZED AT SWITCH POINTS

\[ \eta = \frac{P_L}{P_S} = \frac{Z_L}{Z_S + Z_L} \]

\[ \eta = \frac{P_L}{P_S} = \frac{Z_L}{Z_S + Z_L} \]
COMING UP...

Computer Systems

- Why do computer systems matter?
- Combinational logic
- Sequential logic
- Finite state machines